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Disclaimer

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A report on the deflagration-to-detonation transition (DDT) in the high explosive LX-04

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NAVSEA, Indian Head, MD
Lawrence Livermore National Laboratory, Livermore, CA

Abstract

The deflagration-to-detonation transition (DDT) was investigated for 1.874 g/cc (98.8 % of theoretical maximum density) LX-04 in moderate confinement (4340 steel tube at R_C 32 with 1.020 inch inside diameter and 0.235 inch thick wall) at both ambient initial temperature (roughly 20 ^{0}C) and at an initial temperature of 186 ^{0}C. No transition to detonation was observed in a 295 mm column length for either case.

Introduction

Deflagration and detonation are two distinct modes of combustion possible in high explosives. Deflagration is ordinary "slow combustion". It is propagated by heat transfer, an inherently slow physical process. Detonation is combustion that is propagated by a strong shock wave. Shock waves in condensed materials propagate in the thousands of meters per second range; hence detonation is extremely fast and consequently violent, with detonation in condensed materials propagating at 4000 – 7000 m/s and pressures of 100 – 400 kbar being obtained.

Explosives can be initially ignited in the deflagration mode of combustion and under certain conditions this mode is unstable and will transit to detonation. This transition is undesirable in fuel-oxidizer mixtures specifically designed to deflagrate, such as firearm, rocket, and artillery propellants as well as combustion engine fuel-air charges. Ease of DDT is desirable in primary explosives such as lead azide that are intended to reliably initiate secondary explosives and in fact this is utilized in blasting cap designs. However DDT is generally undesirable in secondary explosives because it posses a safety hazard.

LX-04 is an important high-performance secondary explosive formulation. The 15 wt % Viton A binder very effectively desensitizes the material so that a large improvement in safety is achieved at a modest cost in performance relative to pure HMX.

Here we will address specific safety-related concerns: What happens when a charge of LX-04, confined in a steel vessel, is ignited into deflagration? Will it detonate? Does preheating the sample prior to ignition affect the result? Given the large body of data on other near-full density secondary high explosives (HEs) we felt the likelihood of DDT in the ambient temperature case was very low. However, we were significantly less confident about what would happen in the case of the 186 ^{0}C preheated shot.

Experimental Procedure

LX-04-1 was pressed to 1.874 g/cc in 1.00 inch tall by 1.00 inch diameter pellets from molding powder (LLL serial number B-835). The LX-04 pellets were assembled as a column in a steel confinement vessel using RTV potting compound to fill gaps between pellets as well as between the pellets and the vessel wall. Eleven full length pellets plus one shorter pellet were assembled in shot # 2 to make a column 294.8 mm tall. This leaves just enough room for the ignitor cup. Shot # 3 was loaded with a full pellet less (at the ignitor end) for a column length of only 271.7 mm. This leaves an 8.0 % void at ambient temperature which however should have been completely closed up by the thermal expansion and phase transition volume increase encountered in taking the LX-04 in shot # 3 from room temperature to 186 ^{0}C.

The confinement vessel consists of a 4340 steel tube (heat treated to Rockwell hardness of 32) of inside diameter 1.020 inches and outside diameter 1.490 inches. The tube was 12.00 inches long. 0.65 inch thick flanges were vacuum brazed to each end of the tube. The vessel is sealed by soft copper seals that are crushed between the flange and a 0.75 inch thick steel end cap using eight 3/8 inch 24 threads per inch bolts per end. The confinement vessel hardware is shown in Figure 1.

In terms of the confinement offered by the tube, there are two limiting cases of confinement. For very slow pressurization the yield strength of the vessel is what holds things together. We compute that this tube should rupture at about 1.8 kbar given a yield strength estimate of 5 kbar. This strength estimate would be conservative for this steel at room temperature. It is possible that vessel failure could have first occurred at the end closures but we found in both shots # 2 and 3 that vessel failure apparently occurred in the tube wall. This was the intended way for the confinement to fail.

At the other limit, there is a type of confinement related to the inertia of the wall material that will exist even if the wall material has no strength whatsoever. This inertial confinement confers a relaxation time for pressure on the DDT assembly. This relaxation time is approximately given by the (mass / area of wall) / (sonic impedance of HE). In fact a bare charge can act as its own inertial confinement and this is intimately related to the concept of failure diameter in the detonation of unconfined HE charges.

In fact this is a good point to pursue just a bit further: Without delving deeply into the complex theory of DDT in solid explosives we make use of the widely accepted view that the last step in the DDT process is shock initiation (i.e. a shock-to-detonation, or STD). Suppose we confine the explosive to a rigid tube in which the burst pressure is well above von Nuemann point (this would be satisfied for a detonable gas mixture in a steel tube). In that case the confinement necessary for DDT could be completely supplied by the strength of the tube wall. On the other hand, consider the DDT transition in a bare charge. The confinement must be supplied entirely by the inertia of the charge. If the charge diameter is less than the failure diameter DDT cannot occur because there is simply insufficient confinement even to support the final and most rapid part of the DDT process: steady detonation. If we now consider an intermediate case, the strength of the tube can support the DDT process up to the burst pressure of the tube, but beyond that the confinement necessary to complete the transition must be supplied by the inertia of the DDT assembly.

There is overwhelming experimental evidence from previous studies by many authors over the years that increasing confinement increases the proclivity for deflagration to transit to detonation, in support of the above arguments. Clearly confinement is important to DDT. How then, does one compare the results of this experiment to those of LX-04 in the same physical state, but perhaps in some different geometry of interest?

1) Compare the vessel burst strength of the two confinements
2) Compare the vessel wall mass per unit area of the two confinements (the greater of the two has more wall inertial confinement)
3) Compare the thinnest dimension of the LX-04 charge (the geometry with larger of the two has more self-inertial confinement).
4) If DDT does not happen in geometry A, then it is even less probable in geometries of lesser confinement
5) If DDT does happen in geometry A, then it is even more probable in geometries of greater confinement.

We conducted three experiments here. The first was an intentional detonation of the LX-04 by initiation with an EBW detonator / LX-14 booster (95 % HMX, 5 % Viton A) initiation train. This experiment was conducted to see what the maximum extent of damage to the vessel and witness plate would look like. A diagram of shot # 1 is shown in Fig. 2. The assembled shot is shown in Fig. 3.

The debris from the deliberate detonation shot was very helpful in the assessment of the two shots that followed. The witness plate was shredded and deformed almost beyond recognition. Figure 4 shows the larger witness plate fragments. The most durable witness of fully developed detonation is the end cap farthest away from the detonator. It was recovered mostly in two pieces: the outer ring and the center, which was punched out. This is shown in Fig. 5. The recovered tube wall fragments can be seen in Fig. 6.

Both the second and third shots used a soft ignitor of 75 wt % KNO_3 25 wt % boron. This was loaded in a cup and ignited by a 0.005 inch diameter piece of pyrofuze. This ignitor is intended to ignite the LX-04 charge without a strong pressure build up. We note here that it is actually rather difficult to ignite LX-04 into deflagration. In testing our soft ignitor system we tried several times to ignite a single LX-04 pellet with the pellet held in direct contact with the ignitor but without significant pressure confinement. Although the ignitor would burn quite nicely the LX-04 pellet would simply refuse to ignite. It turns out that the confinement provided by the vessel is critical to successfully igniting the LX-04 in this system.

The second shot was LX-04 at 99 % theoretical maximum density (TMD), held at ambient temperature (roughly 20 ^{0}C). A diagram of the configuration is shown in Fig. 7. The end result is shown in Fig 8. It is gratifying to see that the confinement failure actually occurred in the tube wall, thus the end seals performed their function quite well.

The three most important points to note are that: 1) the tube is almost entirely in two large pieces. 2) The end caps are almost undamaged. 3) The witness plate was recovered almost undamaged. The result is conclusive: There was no transition to detonation in shot # 2. For the details of shot # 2, the reader is referred to the notes of H.W. Sandusky in Appendix A.

The third shot started out with the 99 % TMD LX-04 pellets and we heated the assembly to 186 ^{0}C, allowing room for thermal and phase transition expansion of the LX-04 charge (exactly one full pellet was left out at the ignitor end). We computed that the expanded and delta-phase converted assembly would just fill the tube. Sample temperature was controlled by a commercial oven, which was destroyed in the experiment. Figure 9 is a diagram of the shot. The instrumented shot, ready to go, is shown inside the oven in Fig 10.

Figure 11 show the complete temperature history of the oven and vessel thermocouples. These thermocouples were all mounted externally and the vessel was not penetrated from the outside except for the two wires of the ignitor, which went through the ignitor end cap. Figure 12 is the detail of the same temperature history at the point of the phase transition in the HMX component. Even though the thermocouples are mounted on the vessel exterior the endotherm of this phase transition is clearly seen. This is the endotherm for the beta-to-delta phase transition in HMX. This endotherm seems to be finished at the time of firing, hence we believe that most of the HMX was converted to delta phase by the time the shot was fired.

Figure 13 shows the recovered vessel after the shot. As with shot # 2, the vessel is essentially in one piece, the end caps are essentially undamaged, and the witness plate is essentially undamaged. The conclusion is unambiguous: there was no transition to detonation in shot # 3. Again, for the details of this shot we refer the reader to the notes of H.W. Sandusky (Appendix B).

We had a single strain gauge mounted 50 mm from the ignitor end, and on the tube. The strain history of that gauge is shown in Fig. 14. Most of the strain up to gauge failure occurred in a 0.5 millisecond interval.

In conclusion, We investigated the possibility of DDT in LX-04 loaded at 99 % TMD, both for the case of the LX-04 initially at ambient temperature and for the case of heating the LX-04 to 186 ^{0}C prior to ignition. A 1.00 inch diameter charge approximately 11.6 inches long was used. The steel confinement vessel provided a substantial level of confinement. No transition to detonation occurred in either case. It is even less probable that LX-04 in the same state would DDT under lesser confinements.

The future: We have a number of experiments we plan to execute at NAVSEA, Indian Head MD, as a continuation of this investigation. The Indian Head suite will use both this confinement and a greater level of confinement (1.02 inch inside diameter, 3.00 inch outside diameter steel tube). Three different temperatures (ambient, 160 ^{0}C (just below phase transition), and 190 ^{0}C) and four different densities (60, 75, 90, and 99 % TMD) will be investigated. Appendix C covers the planned Indian Head experiments in greater detail. If DDT is observed we feel it will most likely occur at densities of 60 to 75 % TMD, elevated initial temperatures, and maximal confinement conditions, based on the large body of DDT work on various HEs that can be found in the literature.

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Figure 1: confinement hardware common to all the LX-04 DDT shots performed at LLNL: tube with brazed flanges, and end caps (only one shown). Both end caps are fastened with eight bolts each and sealed with a soft copper ring (not shown).

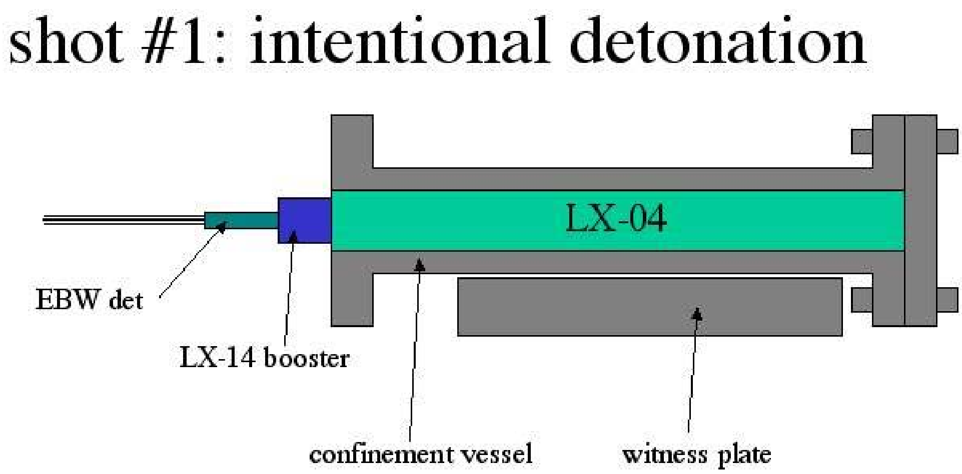

Figure 2: A cartoon of the first shot. In the actual shot the front end cap was bolted on but had a hole drilled through it to accommodate the booster.

Figure 3: The assembled vessel for the first shot, which was a deliberate detonation. The purpose of this shot is to evaluate the level of damage to the vessel and witness plate (strapped below the vessel) expected by fully developed detonation of the LX-04 charge.

Figure 4: The larger pieces of the witness plate, recovered from the intentional detonation.

Figure 5: The end caps from the deliberate detonation. The rear end cap (farthest from ignitor or detonator) is the most durable and reliable witness. It should be punched in two pieces as above right if detonation developed to any extent during the experiment.

Figure 6: The violence of detonation. Larger fragments of the tube wall along with other hardware. The tube wall was completely shattered.

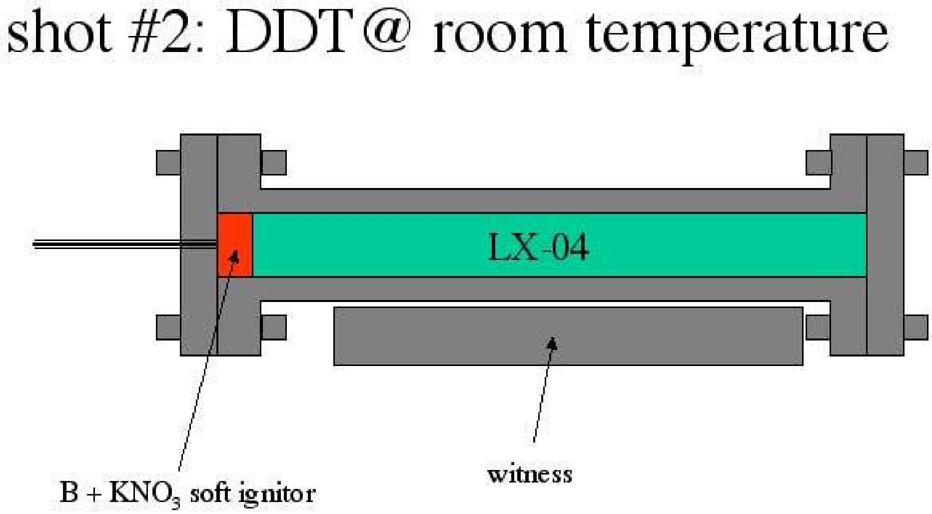

Figure 7: A cartoon of the second shot. Soft ignition was used with the charge at ambient temperature. The ignitor was with 25 wt % boron 75 wt % potassium nitrate. A very small quantity of butyl acetate was sometimes used to facilitate loading the charge in the ignitor cup.

Figure 8: Shot # 2. LX-04 at ambient temperature. The tube came apart mostly in two large fragments. The end caps are intact and the witness plate is virtually untouched. No transition to detonation occurred here.

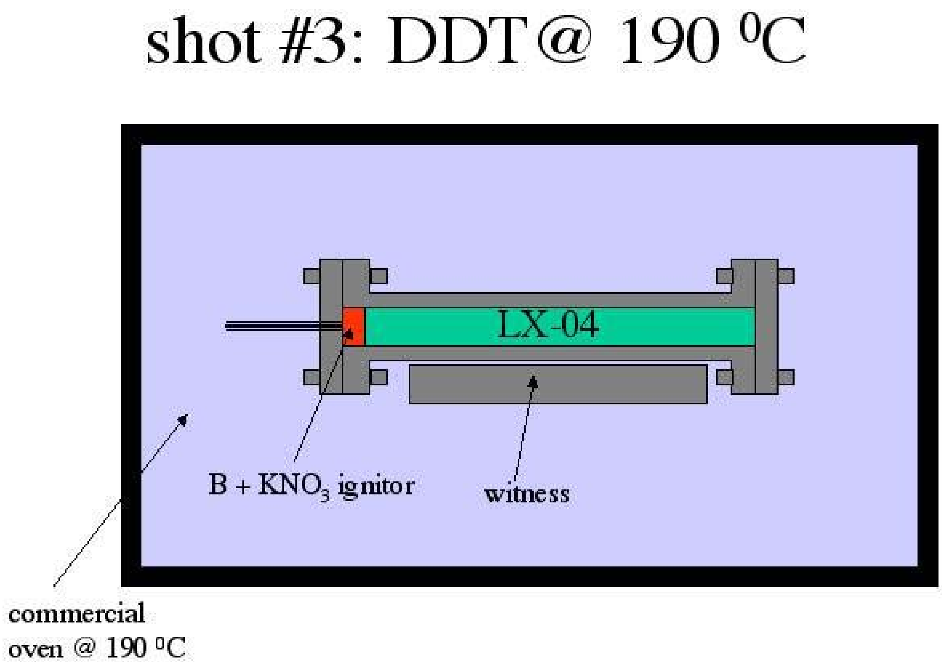

Figure 9: Cartoon of the third shot: soft ignition of LX-04 at 190 ^{0}C (HMX mostly in delta phase). The LX-04 completely filling the vessel interior corresponds to the fully expanded, converted, hot charge. When loaded cold, a full 1.00 inch long pellet was left out at the ignitor end. Thermal expansion together with a solid-solid phase transition of the HMX component causes the charge to expand. We believe the charge freely expanded to just fill, without hydrostatically ramming, the vessel interior at the final conditions just prior to ignition.

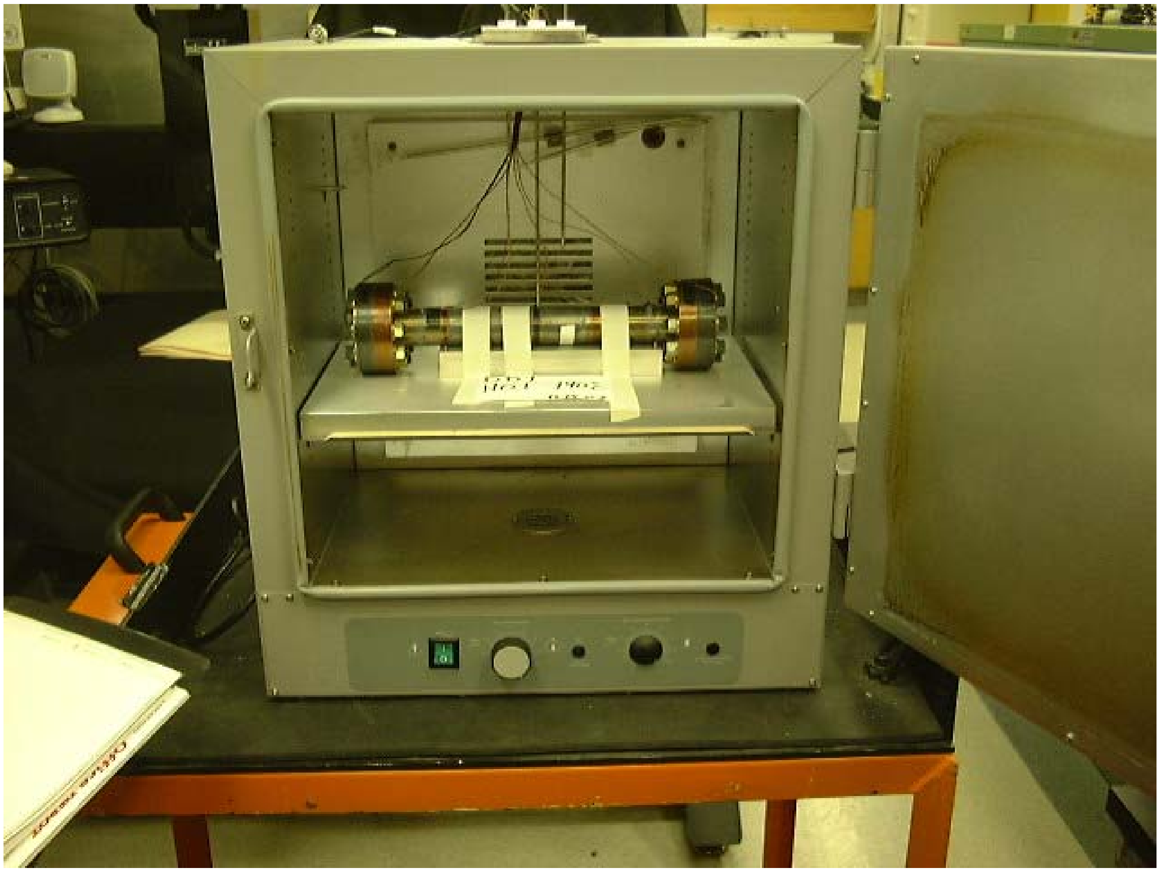

Figure 10: Shot # 3, instrumented and loaded up. LX-04 at 186 ^{0}C, HMX component allowed to mostly convert to delta phase. There were three type K thermocouples suspended above the sample near center to monitor the oven interior temperature near the vessel. Five type K's were mounted on the vessel exterior: 1) directly on ignitor end cap, 2) tube wall at 25 mm from ignitor end, 3) tube wall at vessel center (equidistant from the two endcaps), 4) tube wall at 25 mm from opposite end cap, and 5) directly on the opposite end cap.

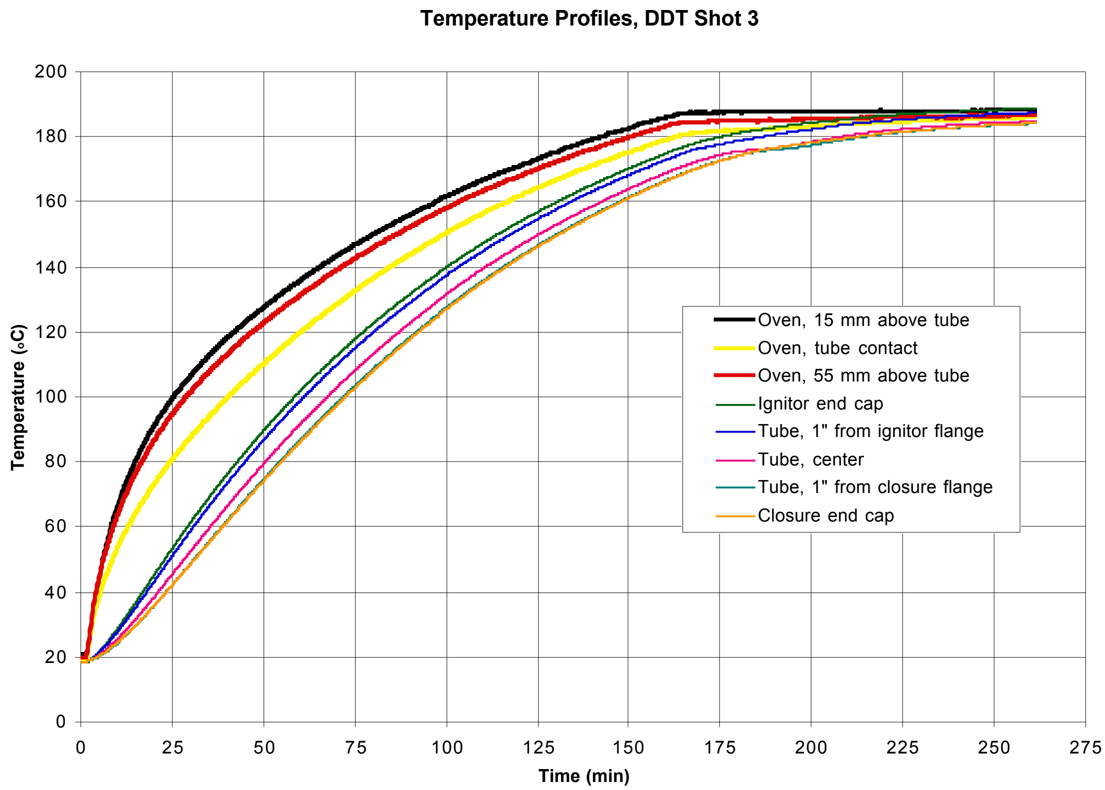

Figure 11: the temperature history of the oven and sample thermocouples in shot # 3. This is the full time record.

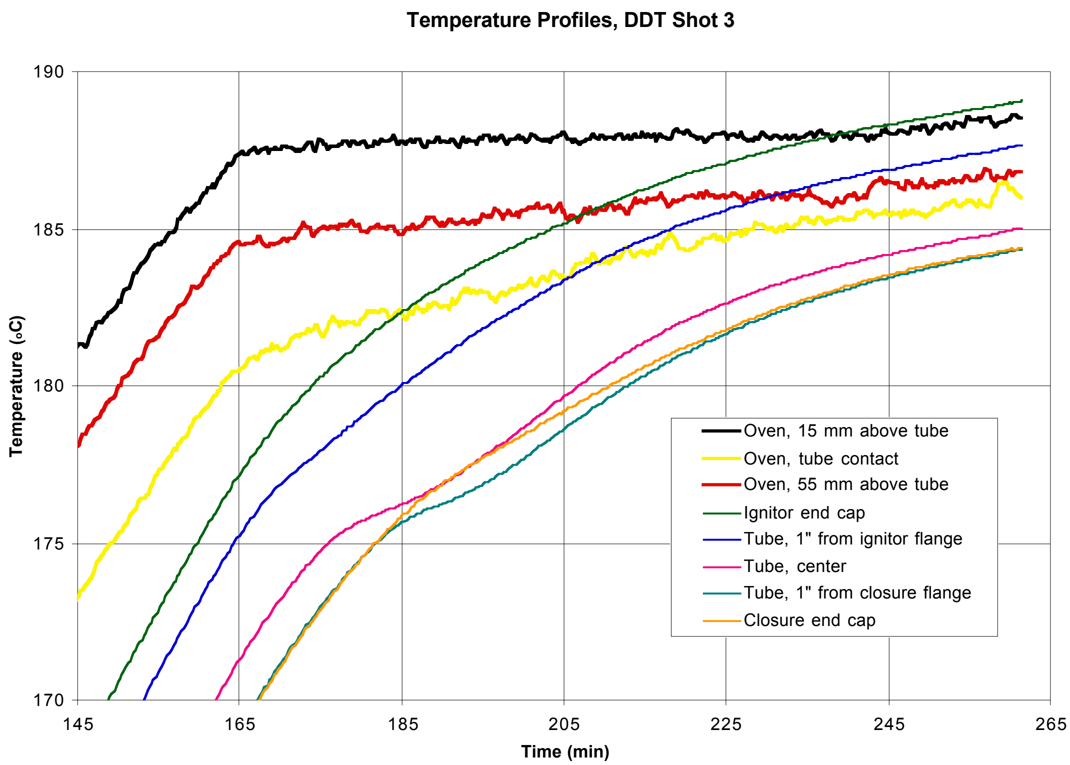

Figure 12: Shot #3: the temperature history for the oven and sample as the LX-04 goes through the HMX beta – delta transition and arrives at the shot temperature. The end of the temperature histories at right is when the shot was fired.

Figure 13: DDT shot # 3. The vessel ruptured cleanly in the wall: one piece. The end caps are intact. The witness plate is untouched. No transition to detonation occurred here. Two Popsicle sticks are used underneath to keep the vessel in position, hence the odd appearance of the left end.

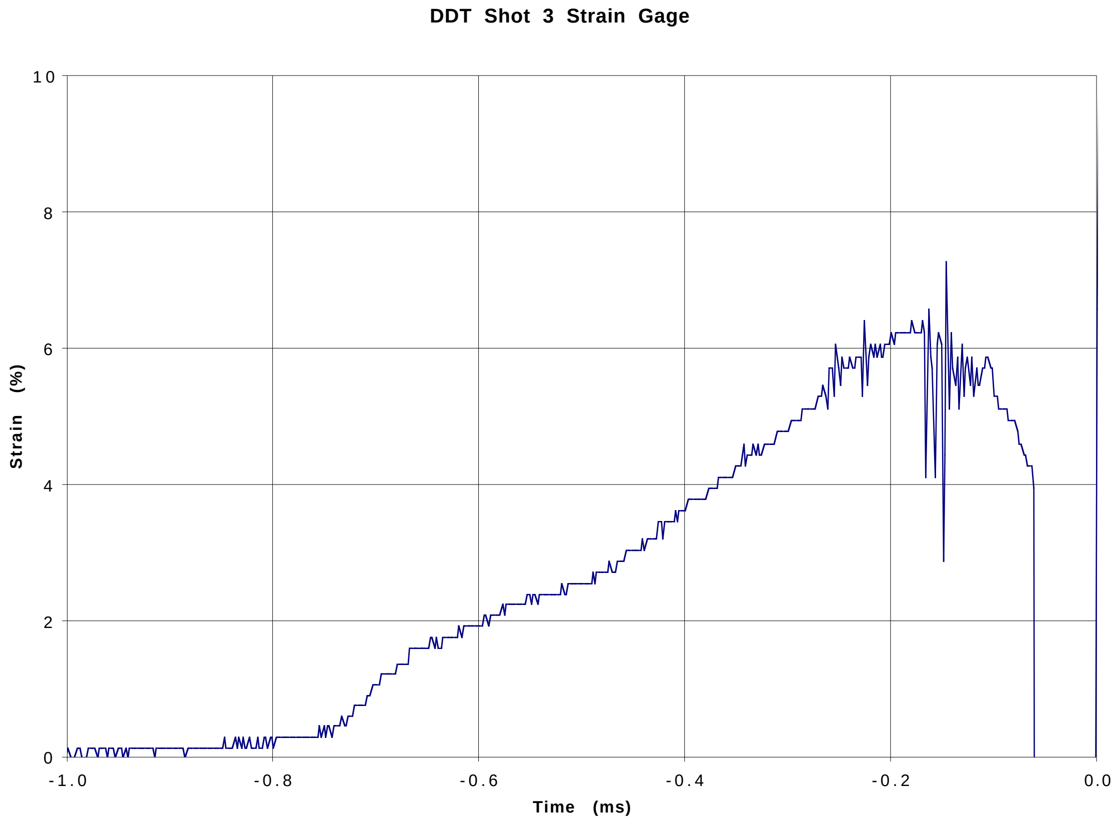

Figure 14: tube wall strain vs. time record for shot # 3. This was the only strain gauge in our three experiments. (We also had one on shot # 2 but we inadvertently destroyed it before it could be used.) It was located 50 mm from the ignitor end cap. The tube growth and rupture process took at least 0.5 milliseconds.

Appendices

Appendix A: H.W. Sandusky's notes on shots # 2.

LX-04 DDT Shot 2

A. <u>Operation</u>: Full density, ambient temperature, LLNL arrangement
B. <u>Lab Form Serial Number</u>: NA, fired at LLNL
C. <u>Date of Experiment</u>: Dec. 16, 2003
D. <u>Experimental Equipment</u>

1. Experimental hardware:

   End cap modified to mate with high-temperature ignitor as shown on attached sketch

   Copper ring (drawing in notebook section on LLNL Arrangement) sealed each end cap to the flange

   70 ft-lbs torque on end cap/flange bolts, starting at 30 ft-lbs and increased in 10 ft-lb increments. Closure end cap was secured before loading LX-04 pellets.

   Red, black, and orange markings placed on tube at 3", 6", and 9", respectively, from ignitor flange. Orange markings also placed on closure flange.

   Witness block (Al, 2" wide x 1" deep x 8 _" long, drawing in notebook section on LLNL Arrangement) under tube, butted against closure flange bolts.

2. LX-04 samples (Batch B-835):

Pellet No.	Mass (g)	Heigth1 (mm)	Height2 (mm)	Dia.1 (mm)	Dia.2 (mm)	Density (g/cc)
042803-11	23.85647	25.362	25.377	25.281	25.282	1.873
042803-12	23.85321	25.358	25.368	25.280	25.282	1.874
042803-13	23.84560	25.378	25.371	25.266	25.270	1.874
042803-14	23.84720	25.366	25.367	25.273	25.289	1.873
042803-15	23.85283	25.356	25.367	25.281	25.283	
042803-16	23.85284	25.359	25.367	25.275	25.277	
042803-17	23.85361	25.361	25.374	25.278	25.284	
042803-18	23.85359	25.367	25.374	25.275	25.279	
042803-19	23.85300	25.360	25.375	25.290	25.282	
042803-20	23.85028	25.366	25.373	25.278	25.274	
042803-21	23.83200	25.348	25.354	25.277	25.281	
120203-2	<u>14.82488</u>	<u>15.769</u>	<u>15.762</u>	25.277	25.279	
Totals	277.17551	294.750	294.829			
		Average =	294.79			

Tube was loaded by pouring in ~1/2 cc of RTV potting compound APC 2.5, inserting a pellet in the order above, pressing the pellet to the bottom with a Teflon ram, and repeating the process. When the loading was complete, a spacer was added on top of the pellets and a 12.33 lb. block was placed on the spacer during curing of the RTV.

Annulus around each pellet = 642.6 mm^3 = 0.64 cc given tube ID =25.91 mm, pellet dia. = 25.28 mm and pellet length = 25.37 mm.

The average of three measurements for cavity depth in the loaded tube was 9.783 mm (as compared to 10.01 mm for a 12.000" long tube with no space between pellets). This was 0.671 mm beyond the end of the ignitor.

3. Ignitor arrangement

Teflon header had a 3/8" dia. circle of 5-mil Pyrofuze. The header had the bridgewire soldered to the leads and then was bonded in the end cap with M-Bond AE-15 epoxy. This process, which was performed at Indian Head prior to shipment of components to LLNL, disturbed the leads passing through the header. Aluminum cup was not used because of concern that the B/KNO_3 would not burn through it.

A new ring was made (drawing in notebook section on LLNL Arrangement) whose ID resulted in an interference fit with the Teflon header and whose height was 9.112 mm, _ mm less than in the original design because of a drawing error.

The first attempt to load the ignitor was similar to that planned with the aluminum cup. A 1-mil thick sheet of Mylar was bonded to one end of the ring with double-backed tape to make a cup, a measured amount of B/KNO_3 was poured into the cup, RTV was applied to the side of the header, and the end cap with bonded header began to be inserted into the ring; but the ring was too tight. The Mylar and B/KNO_3 were removed, and the ring was pressed onto the header with two C-clamps.

The ignitor was loaded by pouring in B/KNO_3 from a weighed container, tamping it, repeating this until the B/KNO_3 was flush with top, and then reweighing the container to obtain the amount loaded (0.50786 g). The ignitor ring was sealed with a 2.5-mil thickness of Mylar tape (Scotch Brand 616 PQX55Y9D4G2).

The bridgewire resistance was measured as 0.277 Ω after loading the ignitor. When connected to the firing line the total resistance was 0.55 Ω.

4. Firing chamber arrangement:

Apparatus horizontally positioned on Al witness block within a steel cylinder (barbette) in the gun tank. The barbette had legs that also extended above the top. There was a sheet of PMMA in the bottom on top of a steel plate. Before firing, another steel plate was placed above the barbette on the extended legs.

One video camera viewed the barbette and another looked into the barbette. Automotive headlamps illuminated the tank.

5. Confinement tube expansion measurement with strain gage (SG):

Upon charge assembly at LLNL, the SG was believed to be open-circuited and so was removed. It was discovered during assembly of Shot 3 that the meter was on the wrong scale, giving the appearance of infinite gage resistance. Gage was probably good.

One gage circumferentially mounted with M-Bond AE-15 at 2" from ignitor end cap

Gage is Micro-Measurements (M-M) Special order C-010905B, which is EP-08-125AC-350 with Option L & 570-28B solder, Gage Factor at ambient temperature (GF_o) = 2.100.

After the gage was bonded, the copper ribbon leads were bent up and then away from the gage by forming them over the stick of a Q-Tip. These leads were potted in a small mound of RTV at the back edge of the gage package. About 0.1" of ribbon lead was exposed before the mound. After the RTV cured, the ribbon leads were trimmed so that they projected ~0.2" from the RTV mound, 24" lengths of 30 AWG solid wire were soldered to the ribbon leads with M-M 450-20S solder (450^{o}F melting temperature), and these junctions were potted to the top of the RTV mound. After this RTV cured, the 30 AWG leads were twisted together and soldered to an~6" length of RG-174 with a BNC connector.

Gage and lead resistance up to BNC connector = 351.1 Ω

Circuit: M-M MR1-350-130 bridge completion module (BCM) with negative signal (S^-) tied to ground, 20 nF capacitor between S^+ and S^- (technique used in previous Shock Validation experiments at LLNL to reduce high-frequency noise on their high bandwidth oscilloscopes), and power input (P^+, P^-) floating. BCM is affixed to +/-5 VDC Polytron Model P33-5-PTS power supply, whose output is 9.96 V. ~10' lengths of RG-174 connected for the SG and the signal.

Bridge calibration with decade box:

Bridge calibration from R = 350 to 450 Ω in 20 Ω increments, with ΔV in volts

$\Delta R/R_o = 0.00011 + 0.39979\ \Delta V + 0.09958\ \Delta V^2$

The coefficient of the second term is the linear bridge constant (BC)

For small strain, $\varepsilon = BC\ \Delta V /GF$

For entire range of strain, $\varepsilon = \Delta R/R_o /GF$

<u>ΔV</u>	<u>%ε</u>	
0.1 V	1.90	
1.0 V	19.0	Small strain assumption
	23.8	Full equation

For a thin wall cylinder, $P\ r = \sigma\ t$, where P is the internal pressure, r is the inner radius (0.510"), σ is the hoop stress, and t is the wall thickness (0.235"). Since $\sigma = E\ \varepsilon$ where E is Youngs Modulus (30 x 10^6 psi), $P = E\ \varepsilon\ t/r$ = (13.8 x 10^6 psi) ε. For P = 3,000 psi, ε = 217 μm/m and ΔV = ε (μm/m)*10^{-3} (m/μm * mV/V)*2.1/0.4 = 1.1 mV. This circuit without amplification is insensitive to pressures less than a kbar.

6. Firing circuit

Modified manganin power supply set for 10 VDC was placed near the tank and triggered for 1 second from the control room. The voltage across the firing line was ~6 VDC. The current viewing resistors (CVRs) were mostly shunted by a wiring error, so that current was not measured. This was corrected following the shot.

With the corrected circuit, a 3-mil Pyrofuze with initially 7 amps of current burst in 16 ms and the 5-mil wire (as used in the shot) with initially 8 amps of current burst in 57 ms.

7. Recording instrumentation:

Only the firing and CVR voltages were recorded.

RESULTS

Arrangement was thrown from the barbette, which helped preserve it from burning of the PMMA plate in the bottom of the barbette over tens of minutes.

The end caps were not deformed and still bolted to the flanges. Half of the tube was still attached to the flanges. The brazing had failed at the closure flange and the tube had shifted out by ~2 mm. The half of the tube still attached to the flanges bulged, the maximum being ~3” from the closure flange. A longitudinal crack that equally divided the attached piece of tube ran from the beginning of the bulge to the closure flange. In addition to the large piece of the tube that separated, there was a ~2” long fragment from between the separated and attached halves that originated between the midplane and 2” toward the closure flange.

The ignitor leads were not blown out of the ignitor flange, but the header and ring were jettisoned.

Appendix B: H.W. Sandusky’s notes on shot # 3.

LX-04 DDT Shot 3

<u>Operation</u>: Full density, heated to ~190^{o}C, LLNL arrangement
<u>Lab Form Serial Number</u>: NA, fired at LLNL
<u>Date of Experiment</u>: Dec. 18, 2003
<u>Experimental Equipment</u>:

1. Experimental hardware:

   End cap modified to mate with high-temperature ignitor as in Shot 2.

   Copper ring (drawing in notebook section on LLNL Arrangement) sealed each end cap to the flange

   70 ft-lbs torque on end cap/flange bolts, starting at 30 ft-lbs and increased in 10 ft-lb increments. Closure end cap was secured before loading LX-04 pellets.

   Red markings on tube at SG and on ignitor flange, black mark on tube at TC6, and orange markings on tube at 3” from closure flange and on that flange

   Witness block (Al, 2” wide x 1” deep x 8 _” long, drawing in notebook section on LLNL Arrangement) under tube, butted against closure flange bolts as in Shot 2.

2. Heating arrangement and temperature measurements with thermocouples (TCs):

   Oven: Sheldon Manufacturing VWR Model 1321F7.5A

   Heating controller programmed to ramp at 10^{o}C/min to 193^{o}C and to hold. Based on the previous Teflon heating, the LX-04 temperature should equilibrate at 190^{o}C. An hour after reaching that state, the shot was to be fired.

<u>TC</u>	<u>Position/Comments</u>
1	Oven control, 14.7 mm above tube
2	Oven, in contact with tube at miplane
3	Oven, 55 mm above tube
4	Ignitor end cap
5	Confinement tube, 1” from ignitor flange
6	Confinement tube, center
7	Confinement tube, 1” from closure flange
8	Closure end cap

   Oven TCs: Three Type K TCs in stainless steel probes on 1” centers mounted in a plug that fit into an opening in top of oven. TC1 was 14.7 mm above the tube, TC2 was on the tube at the midplane, and TC3 was 55 mm above the tube. TC1 and TC3 are switched relative to the Teflon heating test.

Apparatus TCs: Omega cement-on C01-K thermocouple with _ mil thick foil junction and 30 AWG wires. Patch is 3/8” wide x 1” long with a semi-rigid, ~0.1” wide lead. TCs bonded with M-Bond AE-15. TCs on end caps secured with Cincinnati Tool No. 56 Super Jr. C-clamp with a Teflon spacer on the TC and the spindle pad on the inside of the cap. Resistance ≃ 22.5 Ω.

3. LX-04 samples (Batch B-835):

~7% ullage on ignitor end to accommodate expansion from phase change in HMX

Tube was loaded by pouring in ~1/2 cc of RTV potting compound APC 2.5, inserting a pellet in the order above, pressing the pellet to the bottom with a Teflon ram, and repeating the process. When the loading was complete, a spacer was added on top of the pellets and a 12.33 lb. block was placed on the spacer during curing of the RTV.

Pellet	Mass	Heigth1	Height2	Dia.1	Dia.2	
	Density					
No.	(g)	(mm)	(mm)	(mm)	(mm)	(g/cc)
072803-6	23.85701	25.363	25.366	25.268	25.273	1.875
042803-7	23.85406	25.351	25.359	25.277	25.281	1.875
042803-22	23.84608	25.369	25.369	25.273	25.277	1.873
042803-23	23.84949	25.370	25.366	25.274	25.273	1.874
042803-24	23.85271	25.369	25.360	25.275	25.277	
042803-25	23.85236	25.374	25.369	25.273	25.275	
042803-26	23.85162	25.361	25.361	25.274	25.280	
042803-27	23.85260	25.362	25.369	25.276	25.280	
080803-28	23.85088	25.357	25.365	25.278	25.282	
080803-29	23.84880	25.357	25.366	25.275	25.276	
120203-1	16.97305	18.042	18.050	25.280	25.279	
Totals	255.48866	271.675	271.700			
		Average =	271.6875			

The average of three measurements for cavity depth in the loaded tube was 32.990 mm.

4. Ignitor arrangement

Teflon header had a 3/8” dia. circle of 5-mil Pyrofuze. The header had the bridgewire soldered to the leads and then was bonded in the end cap with M-Bond AE-15 epoxy. This process, which was performed at Indian Head prior to shipment of components to LLNL, disturbed the leads passing through the header. One lead projected at least 1 mm beyond the header and was bent over to the side to keep the bridgewire near the header.

As in Shot 2, a modified steel ring was used except that the ID was increased to 0.639 to fit over the header (drawing in notebook section on LLNL Arrangement). After loading 0.39401 g of B/KNO_3 into the ring, its end was sealed by bonding a 1-mil thickness of etched Teflon with RTV 3145.

The bridgewire resistance was measured as 0.33 Ω after loading the ignitor. When connected to the firing line the total resistance was 0.606 Ω.

5. Firing chamber arrangement:

Apparatus horizontally positioned on Al witness block within a steel cylinder (barbette) in the gun tank. This was a larger barbette than in Shot 2 to accommodate the oven. Before firing, another steel plate was placed above the barbette on some bars to leave a gap.

One video camera viewed the barbette and another looked into the barbette. Automotive headlamps illuminated the tank.

6. Confinement tube expansion measurement with strain gage (SG):

One gage circumferentially mounted with M-Bond AE-15 at 2" from ignitor end cap

Gage is Micro-Measurements (M-M) Special order C-010905B, which is EP-08-125AC-350 with Option L & 570-28B solder, Gage Factor at ambient temperature (GF_o) = 2.100.

After the gage was bonded, the copper ribbon leads were bent up and then away from the gage by forming them over the stick of a Q-Tip. These leads were potted in a small mound of RTV at the back edge of the gage package. About 0.1" of ribbon lead was exposed before the mound. After the RTV cured, the ribbon leads were trimmed so that they projected ~0.2" from the RTV mound, 24" lengths of 30 AWG solid wire were soldered to the ribbon leads with M-M 450-20S solder (450^{o}F melting temperature), and these junctions were potted to the top of the RTV mound. After this RTV cured, the 30 AWG leads were twisted together and soldered to an~6" length of RG-174 with a BNC connector.

Gage and lead resistance up to BNC connector = 351.1 Ω

Total resistance up to bridge circuit prior to shot was 351 Ω

Circuit: M-M MR1-350-130 bridge completion module (BCM) with negative signal (S^-) tied to ground, 20 nF capacitor between S^+ and S^- (technique used in previous Shock Validation experiments at LLNL to reduce high-frequency noise on their high bandwidth oscilloscopes), and power input (P^+, P^-) floating. BCM is affixed to +/-5 VDC Polytron Model P33-5-PTS power supply, whose output is 9.96 V. ~10' lengths of RG-174 connected for the SG and the signal.

Bridge calibration with decade box:

Bridge calibration from R = 350 to 450 Ω in 20 Ω increments, with ΔV in volts

$\Delta R/R_o = 0.00011 + 0.39979\ \Delta V + 0.09958\ \Delta V^2$

The coefficient of the second term is the linear bridge constant (BC)

For small strain, $\varepsilon = BC\ \Delta V / GF$

For entire range of strain, $\varepsilon = \Delta R/R_o / GF$

ΔV	%ε	
0.1 V	1.90	
1.0 V	19.0	Small strain assumption
	23.8	Full equation

For a thin wall cylinder, $P\ r = \sigma\ t$, where P is the internal pressure, r is the inner radius (0.510"), σ is the hoop stress, and t is the wall thickness (0.235"). Since $\sigma = E\ \varepsilon$ where E is Youngs Modulus (30×10^6 psi), $P = E\ \varepsilon\ t/r = (13.8 \times 10^6\ \text{psi})$

ε. For P = 3,000 psi, ε = 217 μm/m and ΔV = ε (μm/m)*10^{-3} (m/μm * mV/V)*2.1/0.4 = 1.1 mV. This circuit without amplification is insensitive to pressures less than a kbar.

7. Firing circuit

Modified manganin power supply set for 10 VDC was placed near the tank and triggered for 1 second from the control room. The firing line had 6.10 V at the start, but only a current of 5.16 A through the 5-mil bridgewire, instead of an expected 6.10 V/0.606 Ω = 10.1 A. The burst time of the bridgewire was 335 ms, whereas a bridgewire in a pretest with a starting current of 8.08 A burst in 57 ms.

8. Recording instrumentation:

SG was recorded on Tektronix TDS 540A along with firing and CVR voltages. The SG channel sensitivity was 0.2 V/div with a –1 div BL. The timebase was 20 μs/point for 50 kpts (1 s recording time) with 5% pretrigger.

SG was also recorded on Yokogawa DL 7480 set for 20 MHz bandwidth, 2 μs/pt, 100 ms total recording time. One channel had a sensitivity of 0.1 V/div with a –1 V BL and another channel was set for 1 V/div with a –2 div BL. Scope was internally triggered on the latter channel at +1 V with 50% pretrigger.

RESULTS

Shot was fired with an average temperature on the apparatus of 186°C, which was before the planned temperature of 193°C. The oven had stopped ramping after 165 min at ~187.5°C, stayed relatively steady to 245 min, and then started slowly ramping to ~188.5°C at ~260 min when the shot was fired. (In the Teflon pretest, the oven reached and maintained the control temperature.) The TCs on the tube were increasing all the time, except around ~177°C when the ramping slowed presumably from the HMX phase change. The left end was ~0.5 °C hotter than the oven control when firing, at which time there was a 5 °C difference between the left and right sides of the apparatus. The shot was fired because the temperature of the left end cap began exceeding the oven and the strain gage reading had begun increasing.

The oven was badly damaged but not broken into pieces.

The end caps were not deformed and still bolted to the flanges, but some bolts at the closure flange appear stretched. The tube bulged nearer the ignitor end and split, with the brazing in the ignitor flange failing. The witness was in one piece, with very little damage to it.

SG response is near linear increase from 0.30% at –0.7434 ms to 6.24% at –0.1674 ms, followed by a near linear decline to 4.28% at –0.0634 ms, at which time the gage fails. The gage is still attached to the recovered tube in a region away from a split.

Appendix C: The NSWC continuation of the three LLNL shots

Estimate for DDT Experiments on LX-04 (Draft)

The experiments proposed by Dave Hare in a 11/8/02 draft require development of the arrangement and a technique for preparing samples at 75, 90, and ~100% TMD. These samples are confined in thin and thick steel tubes (low and high confinement) that are opaque to optical or radiographic measurements. Fragment shields will be placed around

the apparatus to prevent damage to the bombproof. These shields may be lined with plastic or plywood, if necessary, to limit damage to the fragmented apparatus.
A summary of the numbers and types of experiments are listed in Table 1, with those requested by Dave Hare using his designations of Series 1A-D. Since experiments at 190°C are planned, both the low and high confinement arrangements need to be developed and evaluated with an inert sample at that temperature, so that the same arrangements can be used for experiments at lower temperatures. This evaluation, listed as Series IH1 and described below in more detail, will include the temperature variation in the apparatus, the viability of the selected diagnostics at 190°C, and functioning of a newly developed ignitor. Series 1A shots are expected to have a pre-detonation column length (ℓ) of less than 10 cm, and will probably be performed in half-length tubes to avoid detonating a long column of HMX. If detonations of LX-04 are not achieved in high confinement, the approach used by Bernecker and Price was to drive the sample with the rapid deflagration of another explosive, which in these experiments could be a short column of the coarse HMX used in the Series 1A shots. These gas loader experiments are listed in Table 1 as Series IH2.

Table 1. Summary of Experiments

Series	Shots	Arrangement
IH1	2-4	Inert in low and high confinement at 190°C
1A	2	Coarse HMX at ambient temperature in 3” tube
1A’	4	~100 %TMD LX-04 in low confinement at ambient & 160°C
1B	2-10	~60, 75 & 90 %TMD in high and possibly low confinement at ambient
1C	2-10	~60, 75 & 90 %TMD in high and possibly low confinement at 160°C
1D	2-10	~60, 75 & 90 %TMD in high and possibly low confinement at 190°C
IH2	0-9	gas loading in high confinement as a function of compaction & temperature
	14-40 (not counting Series IH2)	

Inert evaluations of the low and high confinement arrangements at 190°C, series IH1:

Heating the apparatus: With respect to heating the apparatus, the inert arrangements will have thermocouples on the exterior and within the sample to verify temperature uniformity. There are two approaches to heating the apparatus.

One approach is to find a convection oven large enough to fit the apparatus within. This avoids having to insulate the apparatus and may assist in attaining a uniform temperature, but requires all electrical connections be inside the oven.

The other approach is to attach heating elements on the apparatus and encase it in insulation. The closure plates will probably be redesigned to aid with their heating and the heating of the ends will be separately controlled, both in an effort to avoid the ends of the sample being cooler, which is especially important for the ignitor end.

The proposed diagnostics include ionization pins, strain gages, and a pressure transducer. In all heated experiments, some thermocouples will be required to verify temperature. In addition, all experiments should include a fiber optic probe to verify ignition, as in previous DDT experiments at White Oak.

While co-axial ionization pins have a Teflon-insulated wire within a brass sleeve and are usually connected to Teflon-insulated wire, they are bonded in the tube wall after the sample is loaded (requires hand drilling an ~6 mm deep hole into the loaded sample). The adhesive must cure at room temperature and yet withstand 190^{o}C. These requirements are contradictory for epoxies, whereas the polyester adhesive Micro-Measurements M-Bond 300 can cure within a day, withstands 150^{o}C for transducer applications, and probably is viable at 190^{o}C.

The same techniques for strain gage applications in recent cook-off experiments can be used for the DDT experiments. If tube failure is required versus local strain, then a long gage may be required for circumferentially wrapping around the tube.

Pressure measurements in previous DDT experiments were obtained with piezoelectric transducers with a built-in amplifier, maximum operating range of 8.3 kbar, 1 μs response time, but at a maximum temperature of only 135^{o}C. Without the amplifier, this type of transducer will withstand 204^{o}C, which may be too close to the intended 190^{o}C operating temperature. An alternative is a piezoresistive transducer such as the Kulite HEM-375, which has a 3/8-24 threaded sensor section, maximum pressure range of 1.4 kbar, maximum operating temperature of 260^{o}C, and a natural frequency of 1600 kHz. Thus, frequency response and maximum pressure are low relative to the piezoelectric transducers, and the HEM-375 mounting will weaken a thick wall more than the piezoelectric transducers. The choice of transducer may depend on modeling requirements; for example, high fidelity measurements during the slower and lower pressure deflagration stage may be more important and obtainable with a piezoresistive transducer.

A gasless ignitor is desired. Dave Hare proposed using Ti/B ignited by Pyrofuze. An ignitor that will withstand 190^{o}C has not been located. Code 2210 at Indian Head suggests using a metallic header with glass insulation around the leads, a heavy bridgewire (possibly Pyrofuze), and a porous thermite mix (possibly Ti/B) in an aluminum cup that will readily melt from the thermite reaction.

Pressed samples:

The previous approach at White Oak of pressing samples in increments into the mild steel tubes will not be possible because of the near-TMD density of the LX-04 in the Series 1A’ experiments, even if thick wall tubes were used. To be consistent, pellets whose length is not greater than their diameter will be pressed at 75, 90, and ~100 %TMD in a die/ram set. Machining a thin layer from the ends of pellets pressed at 75 and 90 %TMD can eliminate the preferential pore closure on the ends that otherwise inhibits deflagration near the ignitor. Thus, pressing in a die/ram set and then restoring the porosity to the ends of the pellets offers an advantage over pressing in situ. The disadvantage with inserting already pressed pellets in a tube, versus pressing increments, is that the clearance required for insertion leaves a path for gas flow along the inner tube wall once reaction begins. It may be possible to restrict this gas flow along the inner wall with sealant, possibly high-temperature RTV, but it is difficult to both seal the inner wall and avoid getting the sealant between the pellets. After an initial pressure buildup during an experiment, tube expansion in the ignitor end will open a gap between the inner tube wall and samples no matter how the tube is loaded.

Approach to conducting the experiments by determining the conditions for detonation:

Each of the below steps will be a pre-planned series with samples, apparatus, and instrumentation prepared beforehand. This should be a more efficient approach than completing the experiments in Series 1B, then Series 1C, and finally Series 1D.

1. After conducting the Series 1H1 shots, survey the condition for detonation without diagnostics.
    a. Evaluate coarse HMX at high confinement (Series 1A) and demonstrate what should be mild reaction of LX-04 at ~100 %TMD in low confinement at ambient and 160^{o}C (Series 1A'). (3 shots)
    b. Determine the conditions at which detonation occurs in high confinement. Evaluate ~60 %TMD LX-04 in high confinement at ambient, 160^{o}C, and 190^{o}C; and repeat for 75 and 90 %TMD. (9 shots)
    c. For each condition at which detonation was observed, conduct a comparable low confinement experiment. If detonation was not observed in high confinement, proceed to gas loading experiments without instrumentation in Series IH2.
2. Fully instrument experiments of interest in both high and low confinement.